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Development of figure correction system for inner surface of ellipsoidal mirrors

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ABSTRACT

X-ray mirrors are widely used in advanced x-ray facilities. An ellipsoidal mirror is used in soft x-ray focusing optics. To prevent a decrease in the intensity density or distortion of the wavefront of reflected x-ray beams, the inner surface of an ellipsoidal mirror should have high precision. Differential deposition is a method of fabricating a shape on a mirror surface. However, mirrors with a small diameter cannot be corrected by the conventional process.

In this study, a figure correction method employing ion beam sputtering deposition was developed. The sputtering target is placed inside the ellipsoidal mirror. Then, a cylindrical tube with a small aperture is inserted inside the mirror to realize selective deposition. The figure accuracy of an ellipsoidal mirror is improved even when its diameter is less than 10 mm. This figure correction system can also be applied to various axisymmetric devices with a small diameter.

1. Introduction

X-ray interactions with matter enable us to analyze various properties of unknown materials. For the analysis, specific optical systems have been developed and constructed, which consist of x-ray optical components such as focusing optics and detectors [1,2]. In the x-ray region, the refractive index of materials is small compared with that in the visible region. Mirrors are widely used for collimating, focusing, and imaging in x-ray systems [3–6].

When mirrors are installed in advanced x-ray facilities such as synchrotron radiation and x-ray free electron lasers, their quality should be high because slight surface roughness and a figure error decrease the intensity density and distort the wavefront of the reflected x-ray beams [7,8]. Recently, elastic emission machining (EEM) and ion beam figuring (IBF) have been applied to the fabrication of x-ray mirrors and achieved sufficiently high quality for their ideal performances.

On the other hand, differential deposition based on a sputtering deposition method is means of fabricating a shape or a pattern on a mirror surface [9]. On the mirror surface, a deposition spot is scanned with a variably controlled speed to obtain the desired surface profile. A highly accurate differential deposition system has been developed for the figure correction of x-ray focusing mirrors [10]. In recent years, for the imaging mirror optics in x-ray astronomical telescopes, this technique has been employed as a finishing process [11,12].

An axisymmetric mirror called an ellipsoidal mirror has also recently been developed for soft x-ray focusing (Fig. 1) [13–16]. Soft x-rays can be focused by reflection from the inner surface of the ellipsoidal mirror. The fabrication process, consisting of mandrel fabrication and replication, achieves a root means square (RMS) figure accuracy of better than 15 nm for the mirror surface [17]. However, a theoretical study indicated that an ellipsoidal mirror requires an RMS figure accuracy of 2 nm for ultimate focusing [18]. EEM and IBF cannot be used for figure correction of the inner surface of a mirror. Kiranmayee et al. reported a coating process using radio frequency plasma sputtering for the inner surfaces of tube-shaped mirrors [11]. However, their techniques can only be applied to mirrors with a large diameter.

In this study, we developed a figure correction method using ion beam sputtering deposition with the aim of improving the inner surface of ellipsoidal mirrors with a diameter of less than 10 mm. The sputtering target is placed inside the mirror and scanned so that the figure error profiles is corrected. The developed method is applicable to various axisymmetric mirrors with a small diameter.

2. Apparatus

Fig. 2 shows the concept of the figure correction of tube-shaped mirrors whose reflective surfaces are inside the mirror. This system is based on a differential deposition method using an ion beam gun. To deposit a metal film on the inner surface, a sputtering target is set inside the mirror and sputtered by an ion beam generated outside of the

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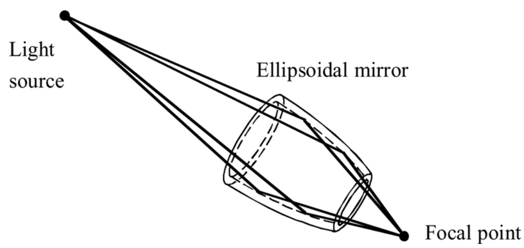

Fig. 1. Schematic drawing of ellipsoidal mirror for soft x-ray focusing.

mirror.

In this study, Ni is selected as the deposited metal. A rod-shaped nickel target is inserted, whose top is cut at an angle of 50°. Ar^+ ions are generated by RF plasma and are accelerated downward in Fig. 2. Then, Ar^+ ions propagate inside the mirror and impact on the Ni target. A cylindrical stainless-steel tube inserted in the mirror prevents the mirror surface from being damaged by direct ion beam irradiation. This cylindrical tube has a Φ1 mm aperture near the surface of the Ni target. Sputtered Ni particles can pass through this hole and adhere to the mirror surface only in a local area. As described later, the deposition spot profile can be decreased by installing this cylindrical tube. The pressure inside the vacuum chamber is kept at around 7×10^{-3} Pa during the sputtering deposition process.

Ni targets are fixed to the motorized rotary and z stages to change the deposition area. This system controls the dwelling time distribution by changing the velocity of the rotary stage as shown in Fig. 2(c).

In deterministic figure correction methods, the dwelling time distribution is calculated by deconvolution using the machining spot profile and the measured figure error profile so that the RMS value of the figure error profile is minimized. In this study, the optimum dwelling time is determined by using the algorithm in ref. [19].

3. Characteristics of stationary deposition spot

In this study, we demonstrated figure correction in only the circular direction, because circular profiles can be measured with high accuracy at the single-nanometer level using a standard roundness measurement machine, even if the measured surface is inside a hole.

In figure correction, the property of stationary deposition is important because the spot size and deposition rate determine the spatial resolution and processing time, respectively. In these experiments, the effectiveness of the cylindrical tube is examined by comparing two stationary spot profiles deposited with and without the cylindrical tube in Fig. 2. The shapes of the deposition spots are measured by the roundness measurement machine, which has repeatability and measurement accuracy at the 10 nm level (EC1550H, Kosaka), as shown in Fig. 3 [20].

Fig. 4(a) shows the cross-sectional deposition rate profiles of stationary deposition spots under the ion beam conditions shown in Table 1, where a conical mirror was used. The deposition time is 15 min. The x axis shows the angles corresponding to the measurement position of the inner surface of the mirror in circular direction. Since the diameter of the circle at the measuring position is 7 mm, 10° corresponds to a distance of 0.6 mm on the circular surface. The exact deposition spot profile is obtained by subtracting the profile before deposition from the profile after deposition. The deposition rate and size are 7 nm/min and 2 mm, respectively. Then, the stationary deposition spot was obtained without the cylindrical tube. In this experiment, a Ni target was fixed on the tip of an Al rod connected to the rotary stage. Fig. 4(b) shows the deposition rate profile, which indicates that the width of the spot profile is increased to 5 mm.

The width of the deposition spot determines the spatial resolution in the figure correction. The spatial resolution is increased with decreasing width of the spot. The merit of a narrow deposition spot was clarified by figure correction simulations. Both the figure error profile of the actual ellipsoidal mirror and deposition spot profiles were inputted into the deconvolution simulator, which outputted the optimum velocity distribution of the rotary stage and predicted the figure error profile after the figure correction. Fig. 5 shows figure error profiles before and after figure correction, predicted by the simulator. The results indicate that the figure error can be corrected to an accuracy of 77 nm in peak-to-valley and that the cylindrical tube with a hole on the wall is necessary. Generally, ion beam sputtering provides low surface roughness. As shown in Fig. 6, an RMS surface roughness of 0.2 nm was confirmed in a square of side 500 nm by atomic force microscopy. This surface roughness is sufficiently low to be used for soft x-ray mirrors from the viewpoint of reflectivity.

4. Figure correction experiments

Figure correction on the inner surface of a conical mirror was demonstrated. The rotation velocity distribution of the Ni target was calculated and inputted into the apparatus shown in Fig. 2. The experimental conditions are the same as those in Table 1. The total deposition time was 177 min. The ion beam system could operate stably for approximately 3 h.

Fig. 7 shows the circumferential profiles measured before and after

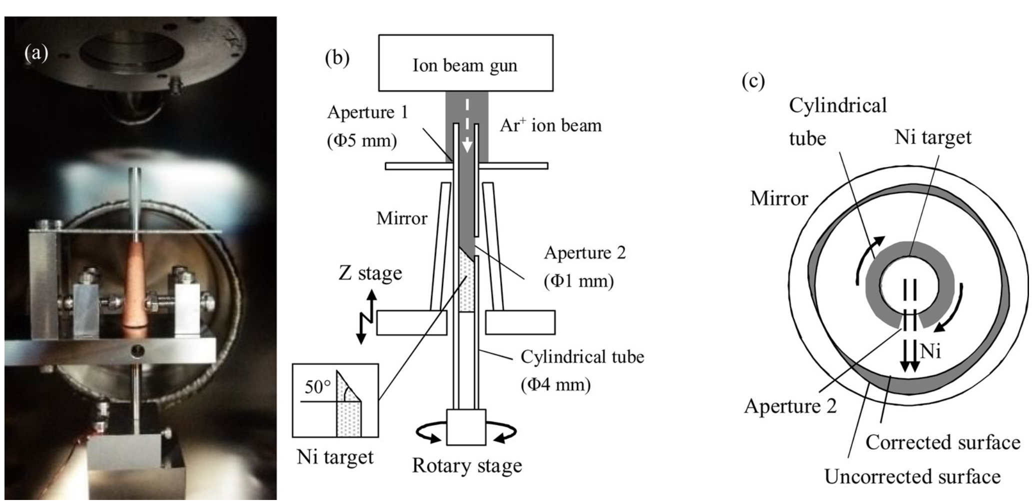

Fig. 2. Concept of figure correction using ion beam sputtering.
(a) Photograph of apparatus. (b) Schematic drawing of the system. (c) Concept of figure correction.